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DO SCALED AND SPECTRUM-MATCHED NEAR-SOURCE RECORDS PRODUCE BIASED NONLINEAR STRUCTURAL RESPONSES?

Paolo Bazzurro[1] and Nicolas Luco[2]

ABSTRACT

Designing new structures or assessing the performance of existing ones is often complicated by the scarcity or absence of real recordings for the earthquake scenarios that dominate the seismic hazard at the site. Scaling real records to a target level or modifying the frequency content and phasing of real records to match a smooth target spectrum are two techniques that are used in practice to address this problem. This article studies the nonlinear response of Single-Degree-of-Freedom (SDOF) oscillators of different periods and strengths subject to real un-scaled records, amplitude-scaled records, and spectrum-compatible records from an intermediate-magnitude, short-distance, forward-directivity scenario. The results show that amplitude (up-)scaling tends to make these records more aggressive than real, un-scaled records with spectra that are naturally at that level. Conversely, the operation of spectrum matching to a smooth target spectrum tends to make these records more benign. The amount of bias and variability reduction depends on the structural period and strength. Engineers should be aware of the possible systematic bias in the nonlinear structural response introduced by these techniques and correct for it, if appropriate.

Introduction

Engineers have used over the years analysis techniques to estimate the seismic performance of new or existing structures located at a specific site. Among the approaches, nonlinear dynamic analysis is believed to provide the most realistic predictions of earthquake-induced structural response. The input ground motions to such analyses are usually selected to be either representative of earthquake scenarios that control the site hazard, or consistent with predefined, "smooth" target elastic response spectra. In both cases, the desired input motions are usually very severe. The scarcity of real recordings with the desired characteristics has often forced practitioners to alter real accelerograms either by scaling (in practice almost always up) the input time histories or by modifying their frequency content to match the desired target.

With either technique, the response prediction accuracy depends on the number, n, of dynamic analyses performed and on the characteristics of the input seismograms selected for such analyses. The minimum number of analyses n necessary to estimate the "median" (calculated as geometric mean) value of a response measure, Y, within a specified accuracy, ζ, is given by:

[1] Manager Engineering Analysis, AIR Worldwide, 388 Market Street, Suite 750, San Francisco, CA 94111
[2] Senior Project Engineer, AIR Worldwide, 388 Market Street, Suite 750, San Francisco, CA 94111 (Now at United States Geological Survey, Golden, CO)

$$n = \left[\frac{\sigma_{\ln Y}}{\eta} \right]^2 \quad (1)$$

where $\sigma_{\ln Y}$ is the dispersion measure used here, namely the standard deviation of the natural log of the response *Y*, and η is the desired level of accuracy (e.g., ±10%).

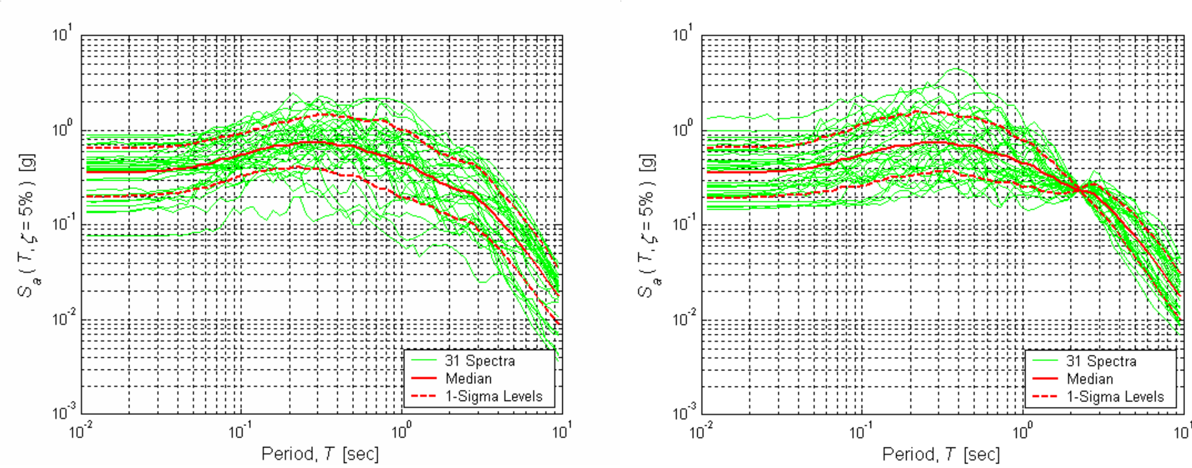
In the last decade, researchers (e.g., Carballo and Cornell 2000) have suggested that the use of amplitude-scaled records and spectrum-matched records is not only legitimate, but also useful, because it limits the number of nonlinear dynamic analysis runs compared to the use of un-scaled, real records without compromising the estimation accuracy. In this article we take a close look at the use of both amplitude-scaled and spectrum-matched records for structural response estimation. We consider a suite of near-source records from intermediate-magnitude events that are altered in both ways, and we statistically compare the structural responses generated by these two sets with those of the original recordings. The primary focus is not on the reduction in response variability, a topic studied before, but on the possible systematic bias that these techniques may induce. To give breadth to the results, we consider a large set of inelastic Single-Degree-of-Freedom (SDOF) systems with different periods and strengths. Additional results for a Multi-Degree-of-Freedom (MDOF) 9-story steel moment-resisting frame are briefly mentioned.

Description of Earthquake Ground Motion Records

Un-scaled (or "Real") Records

We considered a suite of 31 near-source (closest source-to-site distance, R_{close}, less than 16km), strike-normal ground motion components recorded under forward directivity conditions from four different earthquakes: the moment magnitude M_w=6.5 1979 Imperial Valley Earthquake, the M_w=6.7 1986 Superstition Hills Earthquake, the M_w=6.9 1989 Loma Prieta Earthquake, and the M_w=6.7 1994 Northridge Earthquake. All the records have directivity modification factors for spectral acceleration, as defined in Somerville *et al.* (1997), in excess of unity for periods of 1, 2, and 4 seconds. All the ground motions were recorded on NEHRP S_D or S_C sites, and were uniformly processed by Dr. Walter Silva for the PEER Strong Ground Motion Database using a causal Butterworth filter with a high-pass corner frequency less than or equal to 0.2Hz (http://peer.berkeley.edu/smcat/). Note that the selected values of the filter corner frequencies mean that the structural responses are meaningful for all records only for elastic SDOF systems with a period between about 0.00625s and 4.0s. For a few of the 31 records, the nonlinear response of such systems may venture outside of this period range and hence may be driven by noise rather than by “true” ground motion signal. Hence, we will comment on the response results for SDOF systems with fundamental frequency in this period range only.

The 31 records are listed and plotted in Luco (2002). From the 5%-damped acceleration elastic response spectra shown in Fig. 1, Panel a, one can appreciate the large variability in this data set representative of a M_w-R_{close} bin of fairly limited size. For example, the Peak Ground Acceleration, PGA, has more than a tenfold variation from 0.08g to about 0.9g. More formally, the dispersion measure, i.e., the standard deviation of the natural log of the spectral acceleration, S_a, varies with period from 0.5 to 0.85, values consistent with those of attenuation relationships.



(a) (b)

Figure 1. Panel a: Five percent damped elastic response spectra for the original, un-scaled 31 ground motions. Panel b: Spectra for the records that are the amplitude-scaled to match the S_a value of the median elastic spectrum at 2.2 sec. Also shown are the median and the $\pm\sigma$ spectra.

Spectrum-Compatible (or "Spectrum-Matched") Records

The 31 real records were also used as "seeds" for a spectrum matching exercise with the *median* response spectrum from Fig. 1 as the smooth target (see thick solid curve). The median spectrum was selected for reasons that will become apparent later, when we will statistically compare structural responses from different record sets. Nick Gregor[*] and Dr. Norman Abrahamson[**] performed the matching for us by using the program RSPMATCH (Abrahamson 1993). Unlike most codes that generate spectrum-compatible records, this software uses an algorithm that adjusts the original record in the time domain by adding wavelets to it (Lilhanand and Tseng 1988). The resulting spectrum-compatible records each have an elastic response spectrum that is coincident (within a tolerance) with the target median spectrum shown in Fig. 1.

Although the effects on the time traces of spectrum matching via the wavelet technique are quite complex, and the details differ from case to case, two systematic patterns can be detected. In general, the effects on records that are above versus below the target spectrum at long periods are opposite (Fig. 2). This is because the characteristics of the original records in these two sets tend to differ. The former records, on average, have a distinct two-lobe velocity pulse (e.g., Fig. 3, Panel a), whereas the latter ones do not show a clear, long-period velocity pulse (e.g., Fig. 3, Panel c). In the former case, the matching process tends either to remove one of the two velocity pulse lobes or to decrease its amplitude in order to lower the spectrum at longer periods. If the process of lowering the spectrum has also brought the high-frequency part of it below the target, then high frequencies are added back into the signal. Both effects are discernible in Fig. 3, Panel b. In the latter case, the effects are reversed. The desired amplitude levels at long periods are reached by amplifying the entire spectrum, but no long-period pulses are artificially added to the original time history if no pulses were originally there. If this adjusting process causes the high-frequency part of the spectrum to overshoot the target, then high frequencies are removed from the signal. Fig.3, Panel d, shows clearly both effects.

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[*]Pacific Engineering and Analysis, El Cerrito, CA
[**]Pacific Gas & Electric (PG&E), San Francisco, CA

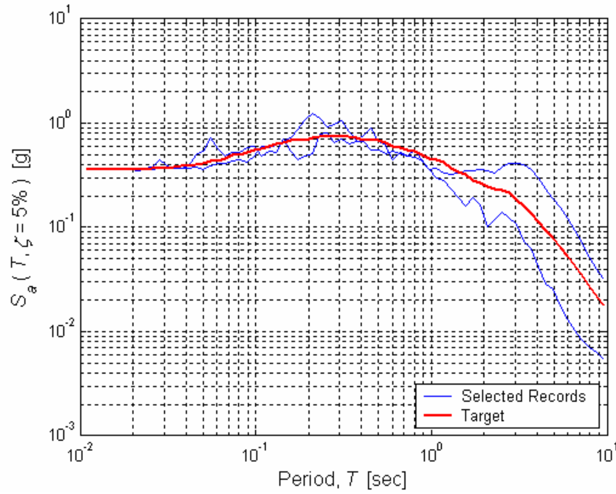


Figure 2. Five percent damped elastic response spectra for the Imperial Valley, El Centro Array #6 Station (above target at longer periods) and Northridge, Sepulveda VA Station (below target at longer periods) records, *before* spectrum matching.

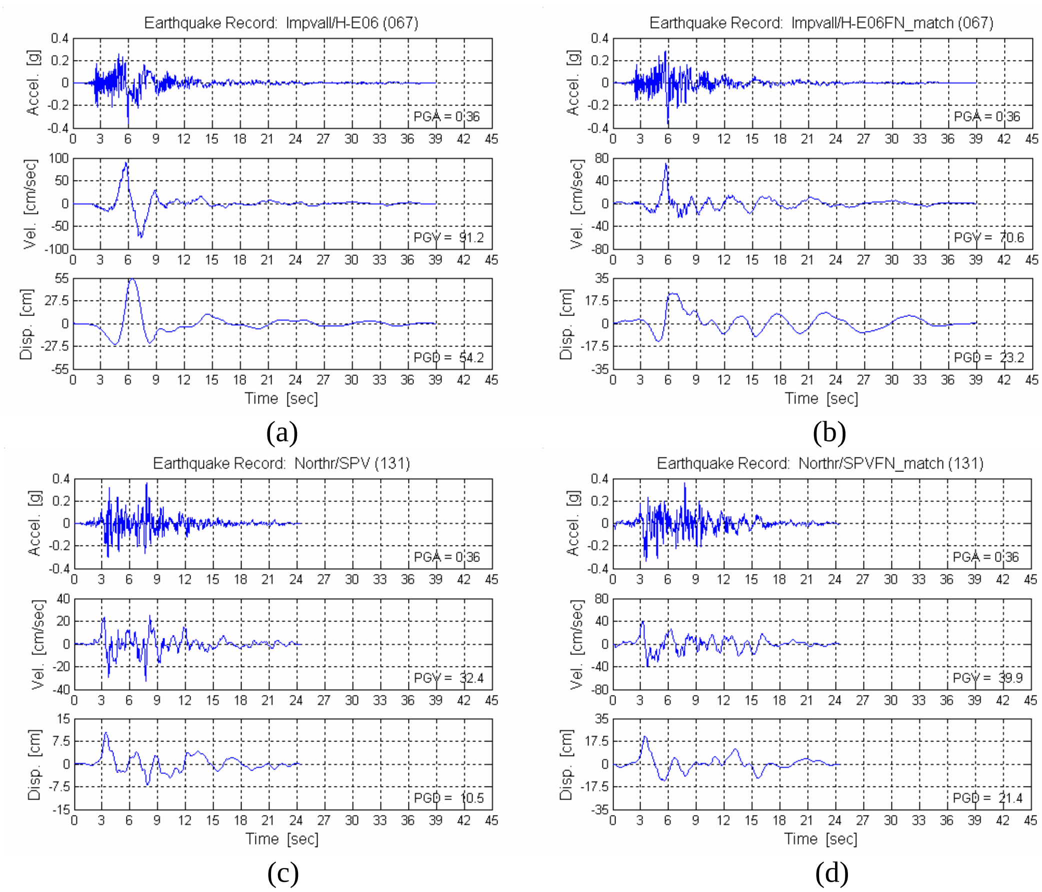


Figure 3. Acceleration, velocity, and displacement time histories of the Imperial Valley, El Centro Array #6 Station record (Panels a and b) and Northridge, Sepulveda VA Station (Panels c and d) record before (left panel) and after (right panel) spectrum matching. Note that the scales of the plots for velocity and displacement are different in the two panels, and that the "before" record has been scaled to the PGA of the "after" record, namely 0.36*g*.

Amplitude-Scaled Records

The real records were also used to create 43 different sets of 31 amplitude-scaled records, one for each of the 43 oscillator periods, T_1, considered between 0.0625s and 4.0s. In each set the records were scaled to match the median spectral acceleration at the given period. Fig. 1, Panel b, shows the scaled response spectra of the data set obtained for the period of 2.2s. By comparing the two panels in Fig. 1 one can see how the resulting "pinching" of the elastic response spectra at T_1=2.2s does not reduce the ground motion record-to-record variability with respect to that of the un-scaled records at periods away from, but not very far from T_1.

Response of Elastic-Perfectly-Plastic SDOF Systems

Description of the SDOF Systems

We analyzed 43 elastic-perfectly-plastic SDOF systems with period, T_1, ranging from 0.0625 to 4.0s, and for each T_1 we considered four different yield strengths, F_y, $F_y^{R=2}$, $F_y^{R=4}$, and $F_y^{R=8}$. For any given value of T_1, the strength, F_y, is the force that corresponds to the yield spectral displacement d_y, where d_y is the *median* 5%-damped spectral displacement at T_1 for the set of 31 real records. The values of $F_y^{R=2}$, $F_y^{R=4}$, and $F_y^{R=8}$ are obtained by dividing F_y by two, four, and eight, respectively. The symbol R in the superscript refers to the strength reduction factor commonly used in building codes. By design, the responses to the 31 real records of the 43 oscillators with yield strengths equal to the values of F_y at each period T_1 are, on average, at the onset of nonlinearity. At the other extreme, the responses of the weaker SDOF systems with yield strength $F_y^{R=8}$ are, on average, severely in the nonlinear range.

Analyses Results

This section presents a distillation of the results of about 16,000 nonlinear dynamic analyses performed on the 43 elastic-perfectly-plastic SDOF systems with four yield strengths levels (F_y, $F_y^{R=2}$, $F_y^{R=4}$, and $F_y^{R=8}$) subject to the three ground motion datasets of 31 records each.

The median displacement response spectra for the un-scaled, amplitude-scaled, and spectrum-compatible ground motions are displayed in log-log scale in Fig. 4. The spectra are presented individually for all four SDOF system strength levels. It is legitimate to assume here that the median displacement response spectrum for the un-scaled records is an *unbiased* estimate of the “true” but unknown median spectrum for this M_w-R_{close} earthquake scenario. As expected given the design of this experiment, the three spectra for the nearly elastic case (i.e., F_y yield strength) are, for all practical purposes, indistinguishable. Hence, as expected no bias is introduced in the elastic (or mildly inelastic) responses by the use of amplitude-scaled or spectrum-matched records. Fig. 4 shows, however, that the median *inelastic* response spectra (namely those for the $F_y^{R=2}$, $F_y^{R=4}$, and $F_y^{R=8}$ yield strengths) for the amplitude-scaled and the spectrum-compatible data sets do not coincide with the unbiased target, particularly at shorter periods. The median spectrum for the amplitude-scaled records tends to be above the target, while the opposite is true for the median spectrum for the compatibilized records. Within the limitation of the sample size used in this study, this discrepancy implies that the use of either amplitude-scaled or spectrum-compatible records introduces a certain degree of bias in the computed structural response. The bias appears to be positive for amplitude-scaled records, which means that the scaling process has made them, on average, *more* aggressive than un-scaled records for the same scenario event. On the contrary, spectrum-matched records appear to be *less* aggressive than their real, un-scaled counterparts (i.e., the bias tends to be negative).

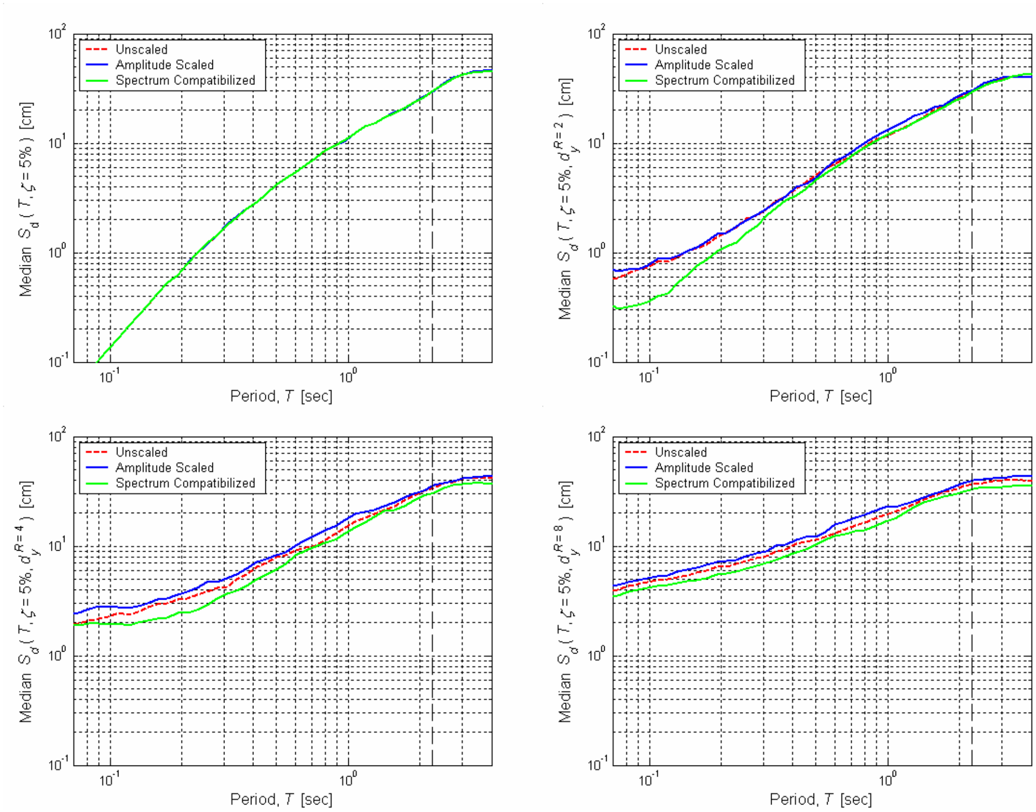


Figure 4. Median inelastic displacement response spectra for the four sets of SDOF systems with strengths equal to F_y, $F_y^{R=2}$, $F_y^{R=4}$, and $F_y^{R=8}$, subject to the three suites of 31 un-scaled, amplitude-scaled, and spectrum-matched ground motions. The dashed line is at 2.2 sec, the fundamental period considered in Fig. 1, Panel b.

Before analyzing these results in more detail it is worth noting again that the limitations in sample size and the relatively large response variability mean that the biases (of opposite signs) introduced by using spectrum-matched and amplitude-scaled records are *not* statistically significant at any customary significance level (e.g., 5% or 10%). The consistency of this bias for all strength levels and all oscillator periods, however, is compelling despite the lack of formal statistical support. The comments that follow are to be interpreted in this light.

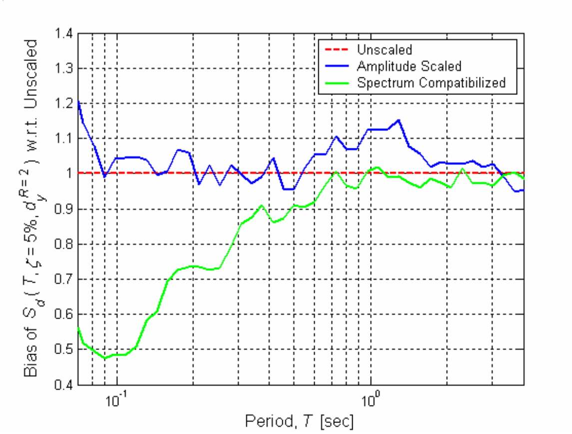
The quantification of the bias is clearer in Fig. 5, which in the left panels shows the ratio of the median spectra from the amplitude-scaled and the spectrum-matched records to the median spectrum from the un-scaled records. The amount of bias across periods is given by the departure from unity. From this figure it is clear that the bias is both *period-* and *yield-strength-dependent*. The bias introduced by amplitude-scaled records for not very severe nonlinear responses ($F_y^{R=2}$ and $F_y^{R=4}$ cases) oscillates in the period range considered between approximately 0 and +25%. The bias tends to stabilize for highly nonlinear responses (i.e., the

$F_y^{R=8}$ case) to about +10% across the entire period range. On the other hand, the bias introduced by spectrum-matched records for moderately nonlinear responses tends to be of the opposite sign and to oscillate from approximately 0 to more than –30% for periods below 0.16s. For severely nonlinear responses, again, the bias becomes approximately constant across period with a value of about –10%.

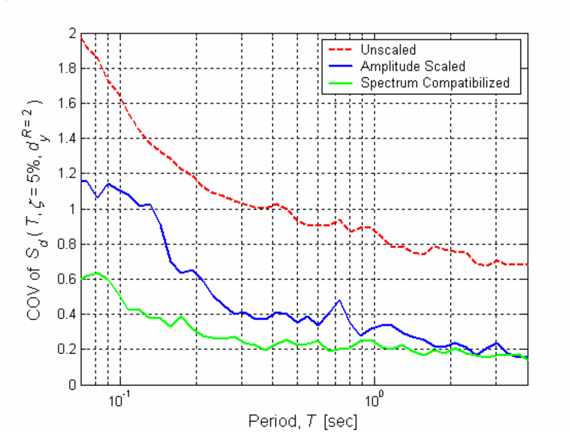
The observed bias generated by spectrum-matched records is in substantial agreement with that reported by Carballo and Cornell (2000). They note that the negative bias may be due to the asymmetric effect that peaks and valleys in the elastic spectrum of real records have on nonlinear structural response. A peak in the period range above T_1 that is larger than the ordinates of the average spectrum for the given M_w-R_{close} scenario tends to make a record more aggressive than average. Conversely, a valley in the period range above T_1 tends to make a record less aggressive than average. The former effect, however, is more pronounced than the latter. Therefore, the spectrum-matching exercise that removes both peaks and valleys to match the smooth target elastic spectrum, in general, artificially renders a record more benign than those in nature.

The qualitative argument that supports the positive bias resulting from amplitude-scaled ones is conceptually similar. Records belonging to the same M_w-R_{close} scenario that need a significant boost to reach the target S_a value are, on average, in a valley at the period (T_1) involved in the scaling process. This means that when scaled up to the target S_a value, such records will show a peak in the period range longer than T_1 that is swept by the structure when entering the post-elastic response regime. In contrast, records that need to be severely down-scaled to the target S_a value at T_1 tend to be, on average, on or near a peak of their jagged spectrum. Therefore, after down-scaling the spectrum will have a valley rather than a peak at periods greater than T_1. As stated earlier, the increment in severity of structural responses introduced by peaks is comparatively larger than the response reduction due to valleys (Carballo and Cornell 2000). This qualitative argument explains, at least partially, the positive bias in the median response of amplitude-scaled records.

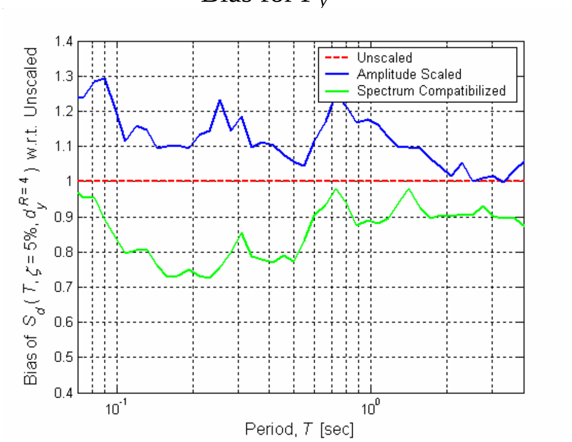
Inspection of the right panels of Fig. 5 confirms that the use of amplitude-scaled and especially spectrum-matched records makes the record-to-record variability in the structural response drop substantially. From a practical standpoint, this translates into a smaller number of analyses needed to reach the same level of accuracy in estimating the median response. This result is particularly useful and somewhat novel for short-period SDOF systems. For those stiff SDOF systems the dispersion of the response for un-scaled records is so large that it prevents the estimation of the median response with reasonable accuracy unless an impractically large number of runs are performed. For example, for the $F_y^{R=8}$ case of a 0.3s SDOF system, about 150 real records would be needed to estimate its median response for this M_w-R_{close} scenario within ±10% (by Eq. 1). Approximately 80 *amplitude-scaled* records and only about 10 *spectrum-compatible* records would be needed to achieve the same level of accuracy.



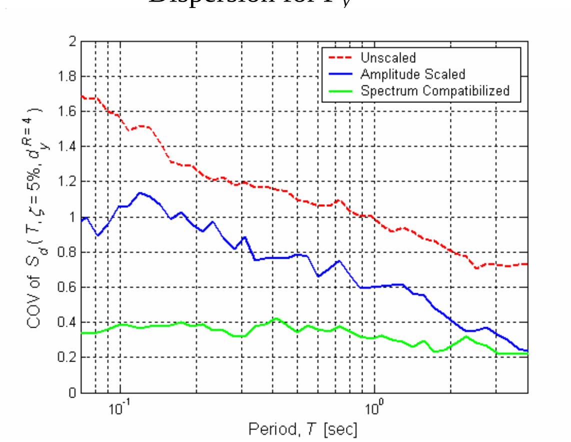
Bias for $F_y^{R=2}$



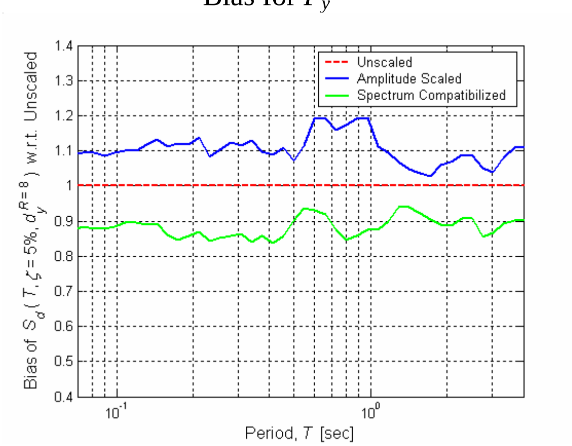
Dispersion for $F_y^{R=2}$



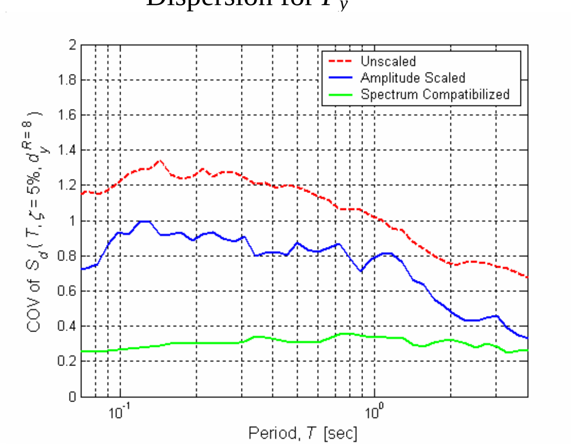
Bias for $F_y^{R=4}$



Dispersion for $F_y^{R=4}$



Bias for $F_y^{R=8}$



Dispersion for $F_y^{R=8}$

Figure 5. Left panels: Bias due to the use of spectrum-compatible and amplitude-scaled records in lieu of real un-scaled records for the three sets of SDOF systems with strengths equal to $F_y^{R=2}$, $F_y^{R=4}$, and $F_y^{R=8}$. The bias is the ratio of the median displacement response spectra (Fig. 4). Right panels: The dispersion (or, approximately, the Coefficient Of Variation) of the inelastic spectral displacements (versus period) for the same three sets of SDOF systems computed using the un-scaled, spectrum-compatible, and amplitude-scaled sets of ground motion records.

Summary and Conclusions

In this study we compared and contrasted the use of real, un-scaled records versus spectrum-matched (or spectrum-compatible) and amplitude-scaled records for the estimation of inelastic response of nonlinear SDOF structures of different strengths and vibration periods. We considered a suite of 31 near-source, forward-directivity ground motion records from intermediate magnitude events that were rotated to be orthogonal to the fault strike. To give breadth to our results we considered elastic-perfectly-plastic SDOF systems with four different strength levels and vibration periods between 0.0625 and 4.0 sec. The responses of all these structures subject to the three different sets of ground motions were evaluated via time-domain step-by-step integration of the equations of motion.

This study is prompted by an interest in real applications. Because of a lack of "appropriate" real records, engineers often resort to using time histories that are either matched to a smooth target spectrum or scaled (in amplitude only) to be "consistent" with a target ground-motion level. The effects that spectrum matching and amplitude scaling have on resulting nonlinear response estimates are, however, not well understood. Here we statistically compared the responses of three sets of "consistent" ground motions representative of the same magnitude-distance (M_w-R_{close}) scenario. The first set is comprised of the 31 real records mentioned above, while the other two are derived from it by spectrum-matching and amplitude-scaling those records to the median elastic spectrum of the batch.

The most important findings of this study can be summarized as follows:

- The use of spectrum-matched records drastically reduces the response variability (by 60% to 80%), which in turn translates into needing many less such records to estimate the median response with the same level of accuracy. This result is especially significant for short-period structures whose large record-to-record response variability practically precludes the use of real accelerograms for response prediction (since more than 100 records may be needed to achieve ±10% accuracy in estimating the median response). The median response to spectrum-compatible records, however, appears to be slightly lower (up to about 30% in some short-period cases) than that caused by real, un-scaled ground motions.
- The use of amplitude-scaled ground motions also reduces the record-to-record response variability, but to a lesser degree (by 20% to 75%). Hence, scaled records that keep their jagged response spectrum are less "efficient" for response estimation purposes than records that have been compatibilized to a smooth target spectrum. Amplitude-scaled records also seem to introduce a bias in the response (up to approximately 25% in some cases), but of opposite sign – i.e., the scaling process appears to make records slightly more aggressive than those in nature.
- Both the bias and variability reduction introduced by using spectrum-matched and amplitude-scaled records vary with severity of nonlinear response and with period of the structure.
- The limited sample size and the large record-to-record response variability prevents us from concluding that the observed response bias is statistically significant at any customary significance level (e.g., 5% or 10%). However, the consistency of our

observations for all structural periods makes for quite a convincing argument. Current research by the authors with more earthquake records will help in this respect.

The results presented in this paper are strictly valid for the near-source records and the SDOF structures considered. They may not necessarily apply to other more ordinary records from a different M_w-R_{close} scenario, and/or to other structures with different characteristics. However, preliminary results (Luco and Bazzurro 2006) obtained for the Phase II SAC 9-story steel moment-resisting frame building designed for Los Angeles conditions (FEMA 2000) and for three "sister" buildings with reduced lateral strengths seem to confirm that most of these findings still hold for a realistic MDOF system. Also, the observations made here on the use of spectrum-matched records are not necessarily applicable to other spectrum-compatibilization techniques. A systematic study on the generality and applicability of these results to other cases is left to future research.

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